Use of Nitrogen-15 Isotopic Techniques to Estimate Nitrogen Cycling from a Mustard Cover Crop to Potatoes

H. P. Collins,* J. A. Delgado, A. K. Alva, and R. F. Follett

ABSTRACT

Farmers in the Pacific Northwest are using cover crops such as white and brown mustards (*Brassica hirta*) in rotation with potatoes (*Solanum tuberosum* L.) because it reduces potential wind erosion and serves as a biocontrol method for a number of plant pathogens. However, there is no information about the N cycling from the mustard cover crop to potato. We used a ^{15}N isotopic crop residue exchange technique to assess this N cycling potential in situ. We conducted two ^{15}N field studies from 2001 to 2004 in the Columbia Basin in eastern Washington on a Quincy sandy (Xeric Torripsamments) soil containing 4 g kg^{-1} soil organic matter under center pivot sprinkler irrigation to assess the fate and N cycling from a mustard cover crop to potato. The established rotation at the site was a winter wheat (*Triticum aestivum* L.)–sweet corn (*Zea mayes* L.)–sweet corn–potato rotation. The aboveground mustard cover crop recovered 34 to 51% of the 56 kg ^{15}N fertilizer applied. The total aboveground biomass and N uptake by the cover crop ranged from 4.6 to 7.5 Mg ha^{-1} and 92 to 142 kg N ha^{-1}, respectively. About 29% of the N in the cover crop was cycled and absorbed by the following potato crop. This study shows that the mustard cover crop can provide 30 to 40 kg N ha^{-1} toward the N requirement of a subsequent potato crop.

The economic viability of worldwide cropping systems is dependent on N availability. Even with the continuing research in N management, average worldwide N use efficiencies (NUE) are reported to be around 50% (Newbould, 1989) and as low as 33% for worldwide cereal production (Raun and Johnson, 1999). These low NUE are in part due to the unique dynamics and mobility of N in the system (Delgado and Follett, 2002). Other reasons for these ranges are the spatial and temporal variability in residual soil NO_3–N and NO_3–N leaching (Delgado, 1999; Delgado and Bausch, 2005; Khosla and Alley, 1999). If these N losses from the N cycle are transported off-site, natural resources may be impacted (Follett and Walker, 1989; Follett, 2001; Follett and Hatfield, 2001). Intensive land use management practices have been reported to contribute to higher groundwater NO_3–N concentrations (Hallberg, 1989; Fletcher, 1991; Spalding and Exner, 1993). Potential off-site NO_3–N transport to water bodies could negatively impact water sources, since the USEPA reported that it is not safe to drink water with concentrations above 10 mg NO_3–N L^{-1} (USEPA, 1989).

Hallberg (1989) reported that some areas of the Pacific Northwest (USA) had the greatest potential for groundwater impacts from N fertilizer use. Other scientists have reported groundwater concentrations higher than 10 mg NO_3–N L^{-1} within the Pacific Northwest including the Central Columbia Plateau (Jones and Wagner, 1995; Ryker and Jones, 1998). Reasons for NO_3–N loading of groundwater include the nature of land use, sandy permeable soils, irrigated systems and planting of shallow rooted crops with high N inputs. One of the crops grown in the Pacific Northwest with high N inputs on irrigated sandy soils is potato. Potato requires adequate N inputs to supply tuber N requirements that range from 90 to 150 kg N ha^{-1} in the Netherlands (Prins et al., 1988); 75 to 127 kg N ha^{-1} in southern Ontario, Canada (Hill, 1986); 135 to 180 kg N ha^{-1} in Wisconsin (Saffigna et al., 1977); 174 to 220 kg N ha^{-1} in Colorado (Delgado, 1999; Delgado et al., 2004); and 212 to 392 kg N ha^{-1} in the Pacific Northwest (Lang et al., 1999; Alva et al., 2002). The wide variation in tuber N requirement is in part dependent on the yield potential in different production systems. Although high N inputs can increase leakage of N from the soil N cycle, it is possible to minimize N losses with nutrient management practices (Hergert, 1986; Meisinger and Delgado, 2002; Shaffer and Delgado, 2002). For example, splitting N applications to one-third to one-half of the annual N rate at planting with the remaining N applied during the growing season in several small doses was recommended to increase N fertilizer use efficiencies for potatoes (Iritani, 1978; Roberts et al., 1991). Another alternative that has been tested on potatoes is to supply N in synchronization with potato N crop demand through the use of controlled release fertilizers (Rosen and Vomuya, 1999; Shoji et al., 2001) with 50% potential reduction in N applied without reducing total tuber yields.

A viable management practice that can increase NUE after shallow root crops, including potato, is the use of cover crops. Delgado (1998) showed that winter cover rye (*Secale cerale* L.) could scavenge residual soil NO_3–N leached below the root zone of shallow rooted crops and return it back to the surface. The use of cover crops to scavenge residual soil NO_3–N from the soil profile to minimize NO_3–N leaching losses has been demonstrated in different crop production systems (Holderbaum et al., 1990; Meisinger et al., 1991; Weinert et al., 2002).

Cover crops can recover 150 to 300 kg N ha^{-1} from the soil profile and return this N to the surface soil (Ditsch et al., 1993; Bundy and Andraski, 2005). The crop residues that have C/N ratios higher than 35 immobilize N reducing the initial N availability to the crop

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Abbreviations: NUE, nitrogen use efficiency; WISE, Washington Irrigation Scheduling Expert.

(Pink et al., 1945, 1948). Doran and Smith (1991) conducted an extensive review and reported that for crop residues with C/N ratios lower than 20, the N mineralizing potential or N fertilizer equivalency is greater than those crop residues with higher C/N ratios. Castellanos et al. (2001) studied the effect of broccoli (*Brassica oleracea* L. Italica Group) aboveground residue that cycled 55% of the broccoli crop residue (126 kg N ha^{-1}) into corn aboveground biomass. Delgado et al. (2004) used ^{15}N and reported that the N cycling or N fertilizer equivalency from aboveground crop residues of barley (*Hordeum* vulgare L.) and wheat, with C/N ratios above 80, was around 12 kg N ha^{-1}. Other scientists showed the N release from wheat residues at about 9 to 10.9% (Fredickson et al., 1982; Porter et al., 1996). Al-Sheikh et al. (2005) reported that increasing the amount of small grain–cover crop residues in a potato rotation increases the potential for N and C sequestration.

Farmers in the Pacific Northwest are using cover crops such as white and brown mustard in rotation with potatoes to reduce potential wind erosion (Bilbro, 1991; Weinert et al., 2002). In addition mustard residues contain glucosinolates that release isothiocyanates after the residue is incorporated in the soil, which reduce the activities of several soil pathogens (McGuire, 2003; Collins et al., 2006). In 2005, mustard cover crop acreage preceding potato exceeded 8000 ha in Washington State, about 10% of the potato acreage in the state. Planted in mid- to late August, white mustard emerges quickly and produces between 5.0 to 7.0 Mg ha^{-1} of dry weight plant residues before succumbing to freezing temperatures, at or near flowering (McGuire, 2003). Although farmers are fertilizing the mustard cover crop with 50 kg N ha^{-1}, an estimate of N cycled from the cover crop to potato is not available. Accordingly, N contributions from the mustard cover crop to the potato N requirement are generally not accounted for in most production systems.

This assessment will increase the accountability of N sources and N transformations in a cover crop–potato rotation, contribute to reducing NO_3–N leaching losses, and account for potential N sequestration in the soil profile. The objective of this study was to follow the fate of N fertilizer applied to a cover crop of mustard preceding potatoes.

MATERIALS AND METHODS

Two ^{15}N field experiments were conducted from 2001 to 2004 at a site near Paterson, WA, on a Quincy sand (Xeric Torripsamments) soil containing 4 g kg^{-1} organic matter under center pivot irrigation. The crop rotation at the site was winter wheat–sweet corn–sweet corn–potato. To avoid potential ^{15}N contamination between studies, Experiment II (Exp. II) was located approximately 1000 m from Experiment I (Exp. I) on the same soil type and under the same crop rotation. The field area was rangeland before cultivation. The site used for Exp. II was cultivated since 1990, while Exp. I was cultivated since 1998. Temperature and precipitation for the 2002 through 2004 cropping seasons were obtained from a permanent weather station located at the site, maintained by the Public Agricultural Weather Stations, Center for Precision Agricultural Systems, Washington State University (Fig. 1). When comparisons were made, statistical analyses were performed using Analysis of variance and Least significant difference procedures (SAS Institute, 1988).

Experiment I: Cover Crop Mustard Nitrogen-15 Study

Plots were prepared in mid- to late August for planting of the mustard cover crop by incorporating sweet corn residues using a rolling cultivator and packer. On 5 Sept. 2001, the cover crop (*Brassica hirta* var. Martigena) was planted using a Brillion planter (Brillion Iron Works, Brillion, WI) at a rate of

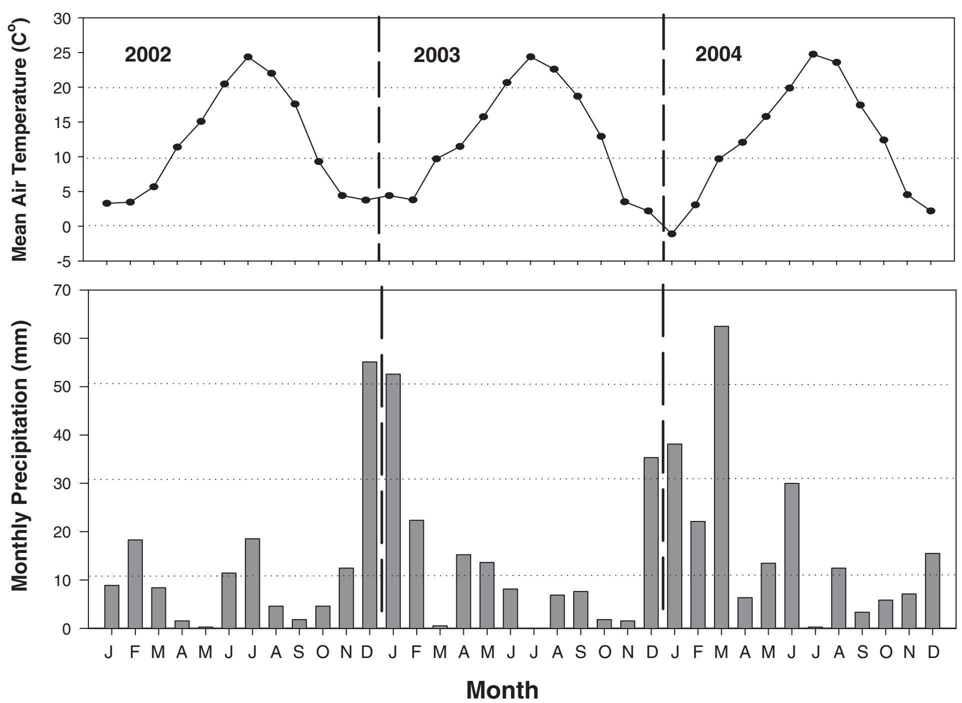

Fig. 1. Average monthly precipitation and air temperatures for years 2002 through 2004.

12 kg seed ha^{-1} in a randomized block design with four replicates. Plots were 5.3 m long by 3.9 m wide with a microplot design that was 3.7 m long and 2.3 m wide (Fig. 2). On 18 Sept. 2001, the plots received 56 kg N ha^{-1} of $^{15}NH_4{}^{15}NO_3$ labeled 10.7204 ^{15}N atom%, using the technique of Follett (2001). Briefly, the solution was added to a 2-L metal tank connected to a compressed air cylinder and applied to the plots uniformly with a pressure maintained at 0.14 to 0.20 MPa. The labeled fertilizer, $^{15}NH_4{}^{15}NO_3$ was applied only to the designated labeled plots (Fig. 2). A second set of nonlabeled plots were established in adjacent side by side pairs (Fig. 2). All nonlabeled plots were treated similarly but for application of 56 kg N ha^{-1} of nonlabeled NH_4NO_3 fertilizer. The plots received no additional fertilizer until before potato planting in March 2002. Nonlabeled plots were used to measure background ^{15}N. To determine the mustard cover crop aboveground biomass, cover crop was cut at ground level on 17 Dec. 2001. Plant samples were collected within a 0.3- by 0.3-m frame from both labeled and nonlabeled plots. Plant samples from the nonlabeled plots were used to obtain the ^{15}N background. Collected plant samples were dried at 55°C for 2 d and weighed for moisture content. Aboveground plant samples from the center microplot area of both ^{14}N and ^{15}N plots were ground and analyzed for total N and ^{15}N. After laboratory analysis, the remaining aboveground biomass from the 0.3- by 0.3-m subsamples were taken back to the field (within 2 wk of sample analysis) and returned to the same place they were collected. The cover crop residue was spread out uniformly over the sample area.

On 4 Mar. 2002 the plots were sampled before cover crop incorporation. Soil cores were taken for bulk densities using a 5-cm-diam. impact core sampler. Soil for chemical analysis was collected from the center of each plot at 0.3 m increments to a depth of 0.9 m using a 7.6-cm i.d. hand auger. Soil samples were kept cool on ice until they were brought into the laboratory. Soil samples were air-dried, ground and analyzed for NH_4–N, NO_3–N, total N, and ^{15}N.

Plant and soil material were analyzed for total N and ^{15}N atom% using a Carlo-Erba automated C/N analyzer (Carlo-Erba, Milan, Italy) coupled to a VG-903 mass spectrometer. The ^{15}N recovery was calculated by subtracting the ^{15}N enrichment from the nonlabeled plots. For each soil sample, two extractions were conducted by weighing duplicate 10 g of soil, extracting with 50 mL of 1.0 *M* KCl by shaking samples for 1 h, and then filtered through a Type A/E glass fiber filter (Gelman Sciences, Ann Arbor, MI). The NO_3–N and NH_4–N in the extracts were determined using colorimetric methods on a flow injection analyzer (Lachat FIA 800 series, Loveland, CO).

On 5 Mar. 2002 mustard residues were incorporated within the surface 20 cm of soil using a small tractor and roto-tiller carefully to avoid movement outside of the plot area. The nonlabeled plots were done first and then residues from the $^{15}NH_4{}^{15}NO_3$ labeled plots were incorporated. One labeled plot was done at a time, with adhering soil and residues removed from equipment by hand before proceeding to the next labeled plots to avoid cross contamination.

Each plot received a blended dry granular fertilizer containing 112 kg of nonlabeled N ha^{-1}, 112 kg P_2O_5 ha^{-1}, and 45 kg K_2O ha^{-1} applied with a Barber spreader (Barber, Spokane, WA) before cultivation. Potatoes (var. Ranger Russet) were planted on 28 Mar. 2002 at an approximate stand density of 45 560 plants ha^{-1} with a two-row potato planter. All plots received a total of 263 kg N ha^{-1} of nonlabeled N (aqueous

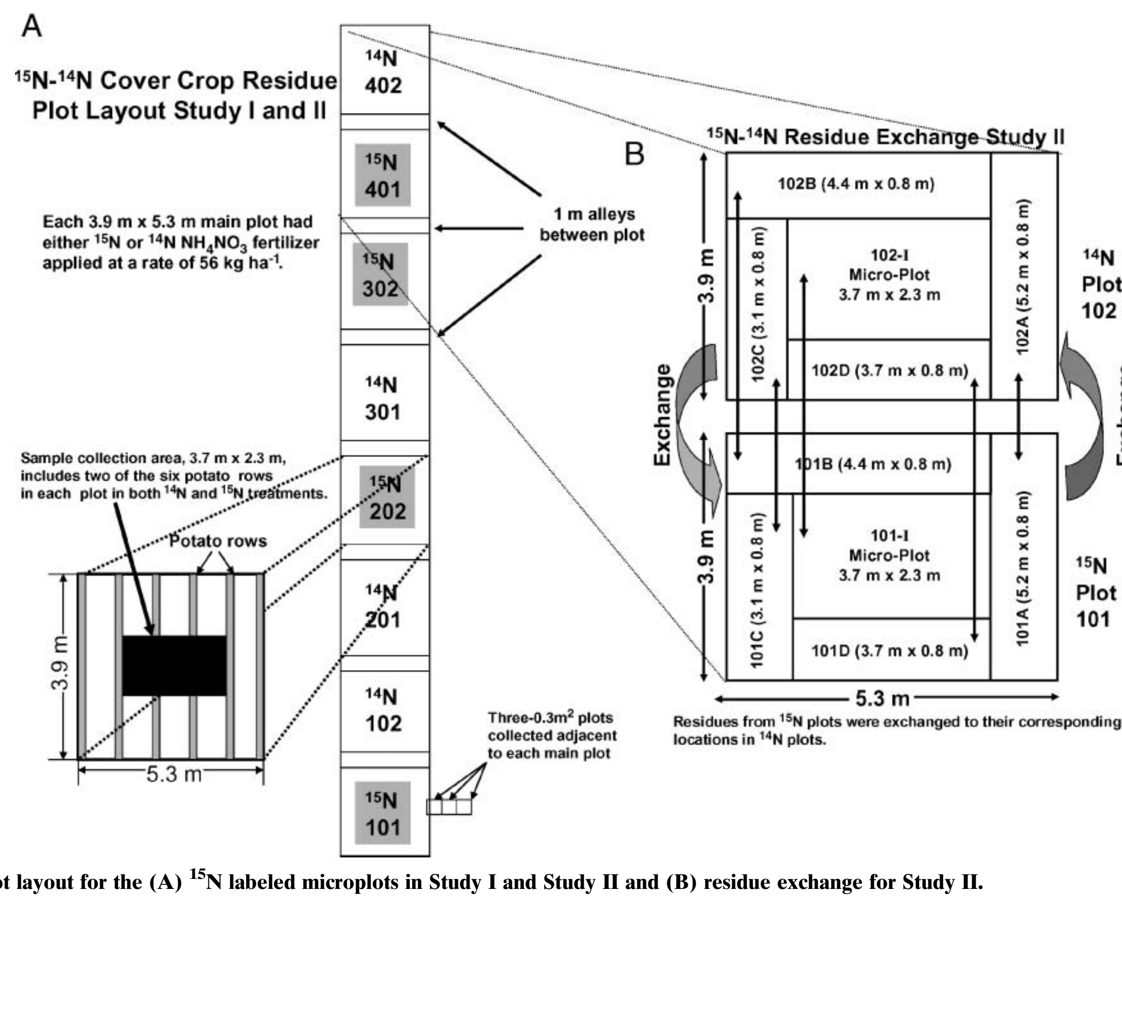

Fig. 2. Plot layout for the (A) ^{15}N labeled microplots in Study I and Study II and (B) residue exchange for Study II.

Urea Ammonium Nitrate, UN32) applied through the irrigation sprinkler system. Approximately, 26 kg N ha^{-1} was applied weekly from 25 May to 15 Aug. 2003. Total sprinkler irrigation for the mustard cover crop and potatoes was 25 and 925 mm, respectively.

To assess N translocation from the vines to the tubers, on 3 July 2002, we collected small amounts of aboveground potato vines. The aboveground biomass of a single potato plant, per labeled and unlabeled plots was collected during the period of initial tuberization near the center of each microplot. At harvest on 11 Sept. 2002, the total N and ^{15}N content of potato vines and tubers were determined by hand digging two potato hills from the center row of the microplot. Plant samples were processed as described above for N and ^{15}N. Tuber yield was determined by harvesting tubers from 3 m of the two middle rows with a one-row Braco digger (Moses Lake, WA) and corrected for removal of the hills used for ^{15}N analysis. Soil samples were not collected after harvest in this study (Exp. I).

Experiment II: Cover Crop Mustard Nitrogen-15 Exchange Residue Study

Nitrogen fertilizer rates, crop management practices, sampling and analyses of soil and plant tissues were similar to those described in Exp. I. As in Exp. I, each ^{15}N labeled plot in Exp. II received 56 kg N ha^{-1} of $^{15}NH_4{}^{15}NO_3$ labeled 10.7204 ^{15}N atom%, using the technique of Follett (2001). For Exp. II soil samples before planting the cover crop were collected in 3 Sept. 2003. The mustard cover crop was harvested on 20 Nov. 2003. Soil samples for total N, inorganic N and ^{15}N were collected on 12 Mar. 2004. Soils were collected during the potato-growing season on 7 July 2004 and after potato harvest on 1 Sept. 2004.

This study was similar to Exp. I with a few minor changes. Soil samples were collected in the hill and furrow positions after potato plants were harvested. Samples were composited and bulk densities measured and the composite sample was processed as above for N and ^{15}N analysis. Potatoes (var. Umatilla) were planted in March 2004 at an approximate stand density of 45 560 plants ha^{-1} with a two-row potato planter. In contrast to Exp. I, we conducted an exchange of the aboveground mustard cover crop residues (Fig. 2). Following cover crop harvest, the labeled cover crop residues were moved and switched with the nonlabeled cover crop in adjacent plots (Fig. 2) using a similar technique and design as done by Delgado et al. (2004). To determine the cover crop mustard aboveground biomass, the microplot area was harvested by sections in November 2003. Sections A, B, C and D with areas of 4.2, 3.5, 2.5 and 3.0 m^2 were harvested and bagged before sampling the center labeled area. The center microplot of 8.5 m^2 was then harvested and bagged. The collected plant material was identified with labels and moved off-site to record the fresh weight. The bagged samples were dried and a representative sample was collected from the bags containing the 8.5-m^2 center microplot area for N and ^{15}N analysis. The residue was then returned to the field within 2 wk of harvesting on 20 Nov. 2003; exchange was made between labeled and unlabeled residue positions and incorporated in March 2004.

On 9 Mar. 2004 before planting of all potato plots, based on a soil test, received 112 kg of nonlabeled N ha^{-1}, 76 kg P_2O_5 ha^{-1}, and 132 kg K_2O ha^{-1} using a Valmar fertilizer spreader (Valmar Air-Flow, Elie, Manitoba, Canada). As in Exp. I, all plots received a total of 263 kg N ha^{-1} of nonlabeled N applied through the irrigation system. Approximately, 26 kg N ha^{-1} was applied weekly from 25 May to 15 Aug. 2004. The total sprinkler irrigation for the mustard cover crop and potato was 92 and 902 mm, respectively. Precipitation during the growing season is shown in Fig. 1. Potato plants and tubers were harvested on 26 Aug. 2004 for yield and ^{15}N determinations as described for Exp. I above. Irrigation scheduling was based on soil profile moisture and measurement of evapo-transpiration. Amount of water applied at each irrigation was determined by the Washington Irrigation Scheduling Expert (WISE) model (Leib et al., 2001).

To complement the field crop residue exchange study, a laboratory mustard crop residue mineralization study was conducted. Air-dried soil, screened to pass a 2-mm sieve was incubated in 0.95-L Mason jars with and without residue addition. There were four replications for each treatment and sample date. Mustard residues were mixed with the Quincy sand soil (917 g kg^{-1} sand, 56 g kg^{-1} silt, 27 g kg^{-1} clay; 4 g kg^{-1} soil organic matter) at the same rate of field mustard residue additions (4600 kg ha^{-1}). Soil water holding capacity was determined using a volumetric soil–water method described by Hook and Burke (2000). Briefly, air-dried sieved (2 mm) soil was packed lightly into 50 cm^{-3}–graduated cylinders and 5 mL of distilled water added slowly. The cylinder was covered with perforated parafilm (American National Can, Greenwich, CT) and allowed to equilibrate. After 24 h, soil volume and water content of the wetted front was determined. Each soil or soil plus residue sample was adjusted to 60% of field capacity and incubated in the dark at a constant temperature of 25°C. The soil and soil plus crop residue samples were extracted with KCl and concentrations of NH_4 and NO_3 determined as described above. The crop residue treated and nontreated soils were extracted at 0, 7, 14, 21, 28, and 35 d incubation periods.

RESULTS AND DISCUSSION

Inorganic Soil Nitrogen

Total soil N content in the surface 30 cm was 1.6 Mg N ha^{-1} for samples collected on 5 Sept. 2001 in Exp. I, and 1.3 Mg N ha^{-1} for samples collected on 3 Sept. 2003 in Exp. II (Table 1). For Exp. I, inorganic N (NO_3–N and NH_4–N) in the top 90 cm of the soil profile were 56.7 and 49.3 kg N ha^{-1} at cover crop planting (September 2001) and before potato planting (March 2002), respectively (Table 2). The corresponding values for Exp. II were 48.6 and 106.6 kg N ha^{-1}. Inorganic N in the surface 90 cm for Exp. II during the potato growing season fluctuated from 106.6 kg N ha^{-1} before potato planting (March 2004), 167.1 kg N ha^{-1} at potato tuber initiation (July 2004), to 68.4 kg N ha^{-1} at potato harvest (September 2004), respectively (Table 2). This data indicates that N fertilizer sources of NH_4–N are rapidly transformed to NO_3–N in these sandy irrigated soils. Around potato tuber initiation (July 2004), below the rooting depth of potato (~50 cm), soil NO_3–N was higher on

Table 1. Bulk density and total soil N for Exp. I and II by 0.3-m depth increments.

Depth	Bulk density	Exp. I†	Exp. II‡
M	Mg m^{-3}	kg N ha^{-1}	
0.0–0.3	1.44	1305 (80)§	1624 (277)
0.3–0.6	1.61	896 (20)	817 (95)
0.6–0.9	1.60	623 (21)	670 (108)
Total	–	2824	3111

† Soil samples collected 5 Sept. 2001.
‡ Soil samples collected 3 Sept. 2003.
§ Values in parentheses are standard error of the mean.

Table 2. Soil NH_4–N and NO_3–N content for Exp. I and II by 0.3 m depth increments.

	Exp. I		Exp. II			
Depth	5 Sept. 2001	4 Mar. 2002	3 Sept. 2003	12 Mar. 2004	7 July 2004	1 Sept. 2004
m	kg NH_4–N ha^{-1}					
0.0–0.3	0.9 (0.8)†	5.8 (1.8)	0.8 (0.2)	3.9 (1.4)	16.8 (4.0)	7.4 (2.0)
0.3–0.6	4.5 (4.2)	3.1 (1.3)	1.7 (0.9)	2.0 (1.0)	11.4 (2.0)	2.9 (1.0)
0.6–0.9	1.3 (1.5)	3.0 (1.6)	1.2 (0.9)	2.0 (1.0)	11.0 (4.0)	2.2 (0.3)
Total	6.7	11.9	3.7	7.9	39.2	12.5
	kg NO_3–N ha^{-1}					
0.0–0.3	28.1 (23.8)	18.8 (14.9)	23.9 (10)	69.7 (21)	76.3 (17)	16.5 (5)
0.3–0.6	9.5 (3.7)	7.3 (5.5)	8.8 (2)	16.8 (7)	28.1 (9)	21.6 (10)
0.6–0.9	12.4 (4.6)	11.3 (6.7)	12.2 (3)	12.2 (6)	23.5 (16)	17.8 (8)
Total	50.0	37.4	44.9	98.7	127.0	55.9

† Values in parentheses are standard error of the mean.

average than samples collected before planting potato (March 2004) or after corn harvest (September 2003) or potato harvest (September 2004) (Table 2).

Biomass Production and Recovery of Nitrogen-15 by Winter Cover Crop

Cover crop biomass production and N uptake in the aboveground biomass were 7.5 Mg ha^{-1} and 142 kg N ha^{-1}, respectively for Exp. II; and 4.6 Mg ha^{-1} and 92 kg N ha^{-1}, respectively, for Exp. I (Table 3). A warmer growing season during Exp. II, unlike Exp. I, contributed to greater aboveground biomass and higher (38%) N uptake in addition to the higher soil NO_3–N on 12 Mar. 2004. The concentration of N in the mustard residue averaged 2.0 g kg^{-1} dry matter for both years. However, N fertilizer recovery by the aboveground cover crop biomass was greater in Exp. I (29 kg ^{15}N ha^{-1}) compared to that recovered during Exp. II (19 kg ^{15}N). Similarly, recovery of ^{15}N fertilizer, in March, in the 0- to 0.9-m soil depth for Exp. I was twice (25.2 kg N ha^{-1}) that of Exp. II (12.3 kg N ha^{-1}) (Table 4 and 5, 0–0.9-m depth). The ^{15}N fertilizer recovered in the cover crop aboveground biomass and soil was 54.2 kg N ha^{-1} for Exp. I, and 32.6 kg N ha^{-1} recovered in Exp. II.

The ^{15}N atom% enrichment decreased with distance from the border of the plot. Figure 3 shows that the distances used for the experimental design for cover crop plots were adequate to maintain the integrity and minimize border effects. The ^{15}N enrichment decreased to background levels after a distance of 0.5 m. Since the borders of the ^{15}N-labeled area microplot were at a distance of 0.9 m from the nonlabeled N fertilizer, we assume that our design adequately simulated N transformations from a mustard cover crop to potato.

Table 3. Mustard cover crop aboveground biomass, N concentration, total N content, total recovery of applied ^{15}N, and percentage N fertilizer recovered for Exp. I and II.

	Exp. I	Exp. II
Biomass, Mg ha^{-1}	4.6 (0.6)†	7.5 (0.5)
N, g kg^{-1}	2.0 (0.1)	1.9 (0.1)
Total N, kg N ha^{-1}	92.0 (13)	142.0 (19)
Recovery of ^{15}N fertilizer, kg N ha^{-1}	29.0 (6)	19.0 (2)
Recovery of ^{15}N fertilizer, %	51.0 (2)	34.3 (5)

† Values in parentheses are standard error of the mean. Mustard crop sampled on 17 Dec. 2002 (Exp. I) and 20 Nov. 2003 (Exp. II).

Yields and Recovery of Nitrogen-15 by Potato

Potato yields were not different between years, averaging 22.3 Mg ha^{-1} dry weight (74.3 Mg ha^{-1} fresh weight) (Tables 6 and 7). Total N tuber uptake in Exp. II was 325 kg N ha^{-1} compared to 219 kg N ha^{-1} observed for tubers in Exp. I. The 65 kg N ha^{-1} found in potato vines in Exp. II on 26 Aug. 2004 was also higher than the 42 kg N ha^{-1} ($P < 0.05$) found for Exp. I on 11 Sept. 2002. Total N uptake (tubers + vines) was 17.2 and 11.9 kg N Mg^{-1} dry tuber weight for the Umatilla (Exp. II) and Ranger (Exp. I), respectively. Total fertilizer N applications were 375 kg N ha^{-1} for Umatilla and Ranger, respectively.

Potato vines recovered 10.1 kg N ha^{-1} of the applied ^{15}N fertilizer (Table 6) in Exp. I during the initial period of tuberization (3 July 2002). The ^{15}N fertilizer recovery in the vines at harvest was 2.1 kg N ha^{-1}. This difference of 8.0 kg N ha^{-1} is similar to the tuber ^{15}N content at harvest of 10.4 kg N^{15}N ha^{-1}. Assuming that the 8.0 kg N ha^{-1} was translocated from the vines to the tubers, this would be equivalent to a transport of 79% of the vine N on 3 July 2002, or an equivalent of 116 kg N ha^{-1} to the tubers. These data agree with Lauer (1984) who conducted N management studies under irrigation for potatoes grown on a similar soil. Lauer (1984) evaluated rates of N fertilization ranging from 100 to 600 kg ha^{-1}, with an initial application of 100 kg N ha^{-1} before planting and the rest split over several sprinkler applications. Similarly, Lauer (1984) reported a higher N sink at or near the onset of tuber formation, while previously the vines had a higher N uptake rate.

Nitrogen-15 Crop Exchange Residue and Crop Residue Mineralization Studies

The total N added to the plots from the ^{15}N labeled crop residue, Exp II was 19.0 kg N ha^{-1} (Table 3). Of the

Table 4. Total recovery of applied ^{15}N fertilizer and percentage N fertilizer recovered for Exp. I by depth increment (4 Mar. 2002).

Depth	Recovery of ^{15}N fertilizer	
m	kg N ha^{-1}	%
0.0–0.3	12.6 (4.0)†	23 (0.09)
0.3–0.6	8.2 (2.0)	15 (0.08)
0.6–0.9	4.4 (1.0)	8 (0.08)

† Values in parentheses are standard error of the mean.

Table 5. Recovery of applied ^{15}N fertilizer from soil for Exp. II by depth increments for plots initially labeled with ^{15}N fertilizer application and for plots receiving labeled ^{15}N crop residue.

	Plots initially label with ^{15}N fertilizer (soil and roots)			Plots receiving ^{15}N labeled mustard residue (aboveground biomass)	
	Recovery of ^{15}N fertilizer				
Depth	12 Mar. 2004	7 July 2004	1 Sept. 2004	7 July 2004	1 Sept. 2004
cm	kg N ha^{-1}				
0.0–0.3	8.8 (1.2†)	6.0 (0.4)	9.1 (1.4)	7.3 (3.8)	8.3 (2.9)
0.3–0.6	1.7 (0.4)	0.6 (0.2)	1.4 (0.8)	1.4 (0.4)	2.7 (1.0)
0.6–0.9	1.8 (0.6)	0.7 (0.3)	1.0 (0.4)	0.5 (0.2)	1.5 (0.3)
0.9–1.2	1.3 (0.6)	0.4 (0.2)	ND	1.3 (0.7)	ND
Total	13.6	7.7	11.5	10.5	12.5
	%				
0.0–0.3	15.8 (2.2)	10.5 (0.6)	16.2 (2.5)	13.1 (6.9)	14.9 (5.2)
0.3–0.6	3.0 (0.6)	1.1 (0.4)	2.8 (1.4)	2.4 (0.8)	5.0 (3.6)
0.6–0.9	3.3 (1.0)	1.3 (0.6)	1.8 (0.6)	1.0 (0.4)	2.7 (0.5)
0.9–1.2	2.6 (1.3)	0.7 (0.4)	ND	2.3 (1.3)	ND

† Values in parentheses are standard error of the mean. ND, not determined.

^{15}N fertilizer contained in the aboveground cover crop biomass, 4.8 and 0.8 kg N ha^{-1} was taken up by the potato tubers and vines collected at harvest, respectively (Table 7). At harvest, total recovery of applied ^{15}N fertilizer for Exp. II for the plots initially labeled with ^{15}N fertilizer was 2.6 and 0.4 kg N ha^{-1} for the tubers and vines, respectively (Table 7). The total recovery of the initial ^{15}N fertilizer applied between the residue exchange plots for Exp. II, showed recoveries from aboveground biomass and soil compartments to be 8.6 kg N ha^{-1} compared to the 12.5 kg N fertilizer ha^{-1} recovered during Exp. I.

We used the total ^{15}N recovery from the residue exchange plots (Exp. II) to estimate the N uptake from the mustard crop residue. Since 19.0 kg ^{15}N ha^{-1} was added as aboveground biomass to the residue exchange plots and recovery of ^{15}N was 5.6 kg ^{15}N ha^{-1} by the potato tubers and vines at harvest, we can account for 29% recovery of N from the cover crop residue {[4.8 kg ^{15}N ha^{-1} tubers (Table 7) + 0.8 kg ^{15}N ha^{-1} vines; Table 7] ÷ [19 kg ^{15}N ha^{-1}crop residue; Table 3] × 100 = 29%}. About 66% of the N from the crop residue recovered in the soil while 29% was cycled to the following crop. Only 5% was not recovered, in agreement with Delgado et al. (2004) and Al-Sheikh et al. (2005) who reported that crop residue N that can be sequestered in the organic matter and or cycled to the following crops of potato rotations. Assuming similar release and uptake rate between the ^{15}N and N in the cover crop mustard residue, this is equivalent to a potato uptake of 40.6 kg N ha^{-1} from the N in the aboveground cover crop mustard residue grown on these plots. Since commercial N fertilizers have a lower NUE (50%) (Newbould, 1989), this recovery may be equivalent to a fertilizer application of 80 kg N ha^{-1}.

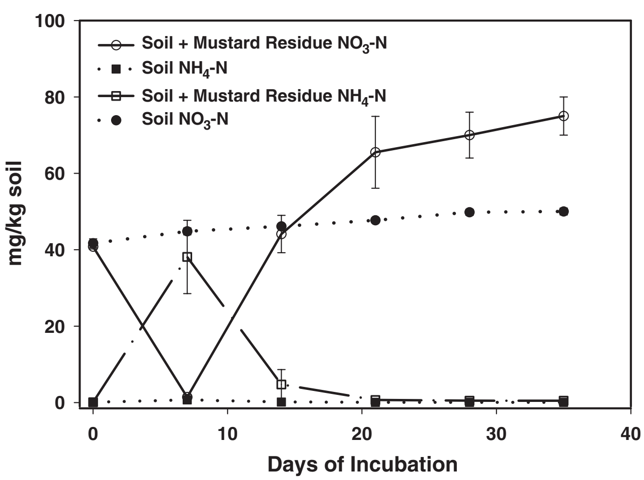

Fig. 3. Amount of N mineralized from mustard residues during a 35-d laboratory incubation. Values are averages of four replicates, bars are standard error at $p = 0.05$.

Table 6. Biomass (dry weight) and N content of potato vines and tubers from N applied to the mustard cover crop in Exp. I.

	Vines		Tubers‡
	3 July 2002	11 Sept. 2002	11 Sept. 2002
Biomass, Mg ha^{-1}	3.1 (0.2)†	2.9 (0.1)	21.9 (1.0)
N, g kg^{-1}	47.9 (1.9)	14.3 (0.7)	10.0 (0.2)
kg N ha^{-1}	148.5 (11)	41.5 (2)	219.0 (9)
Recovery of ^{15}N fertilizer, kg N ha^{-1}	10.1 (0.1)	2.1 (0.5)	10.4 (0.4)
Recovery of ^{15}N fertilizer, %	18.0	3.8	18.6

† Values in parentheses are standard error of the mean.
‡ Tubers dried to 30% moisture content.

For Exp. II, 22% of the N fertilizer applied remained in 0 to 0.9 m of soil at the time of cover crop mustard incorporation (Table 5). There was no initial loss of N from the plots labeled with ^{15}N fertilizer during the potato-growing season since 12.3 kg ^{15}N fertilizer ha^{-1} was found in the soil (0–0.9 m) at incorporation of the mustard cover crop in the spring (March 2004) and a total recovery of 12.5 kg ^{15}N at harvest (Table 5). This result agrees with those of Delgado et al. (2004) who suggested that the residual ^{15}N fertilizer recovered before potato planting was associated with the stable organic fractions. These results of high N immobilization in the soil from the crop residue agree with results from Al-Sheikh et al. (2005) who found that rotations for small grain–potato systems (when all the crop residue is incorporated) sequester N in the particulate organic matter for irrigated, N-fertilized sandy arid soils.

The crop residue laboratory mineralization study showed that about 25 mg N kg^{-1} (36 kg N ha^{-1}, using a bulk density of 1.44 Mg m^{-3}; Table 1) was mineralized from aboveground mustard residues over a 35-d laboratory incubation (Fig. 4). This laboratory incubation study supports the field ^{15}N residue exchange results of Exp. II where 40 kg N ha^{-1} was available to the potato crop. This suggests laboratory incubations may index potential N contributions from mustard cover crops.

Nitrogen Dynamics for Cover Crop–Potato Systems

For Exp. I the aboveground cover crop N uptake of 92 kg N ha^{-1} (Table 3) plus the 4 Mar. 2002 residual soil inorganic N of 49.3 kg N ha^{-1} (Table 2) was 141.3 kg

Table 7. Biomass (dry weight), N content and ^{15}N recovery in potato vines and tubers at harvest from N applied to the mustard cover crop in Exp. II. Plots were harvested 26 Aug. 2004.

	Vines	Tubers	Vines	Tubers
	Plots label with ^{15}N fertilizer (soil and roots)		Plots receiving ^{15}N labeled mustard residue (aboveground biomass)	
Biomass, Mg ha^{-1}†‡	2.3 (0.1)	22.8 (2.0)	2.3 (0.2)	22.7 (1.0)
N, g kg^{-1}	29.2 (3.9)	14.8 (0.6)	28.2 (3.4)	14.3 (1.8)
kg N ha^{-1}	67.2 (11)	337.4 (23)	64.9 (9)	324.6 (35)
Recovery of ^{15}N fertilizer, kg N ha^{-1}	0.4 (0.1)	2.6 (0.8)	0.8 (0.2)	4.8 (1.7)
Recovery of ^{15}N fertilizer, %	0.7 (0.1)	4.6 (1.5)	1.4 (0.4)	8.6 (3.0)

† Values in parentheses are standard error of the mean.
‡ Tubers dried to 30% moisture content.

N ha^{-1}. Total N input for Exp. I were 56 kg N fertilizer ha^{-1} plus 56.7 kg N ha^{-1} found in the initial inorganic soil N pool in September 2001, for a total N of 112.7 kg N ha^{-1} (Table 2). Assuming zero N losses, at least 28 kg N ha^{-1} must have been mineralized to balance N inputs and sinks. Similarly, for Exp. II aboveground cover crop N uptake was 142 kg N ha^{-1} (Table 3) plus the March 2004 of 106 kg N ha^{-1} (Table 2) for soil inorganic N was 248 kg N ha^{-1}. Total N inputs of 56 kg N ha^{-1} to the mustard, 112 kg N ha^{-1} fertilizer added at preplant, plus 48.9 kg N ha^{-1} initial soil inorganic N content yields an N source of 217 kg N ha^{-1}. The difference of 31 kg N ha^{-1} (248 kg N ha^{-1}–155 kg N ha^{-1}) must have been mineralized during the course of the cover crop season, possibly from unsampled mustard root materials or other crop residues produced in the rotation.

These estimates between N inputs and N sinks suggest that there are other N sources (such as the sweet corn residues) in the system that need to be accounted for to improve the 30 kg N ha^{-1} shortfall in N accounting. Analysis of sweet corn residues showed them to contain 7.5 g N kg $^{-1}$ residue that could provide an additional N source of 33.4 kg N ha^{-1}. This is similar to the amount needed to balance sources and sinks. Weinert et al. (2002) reported that N mineralized from cover crop residues is rapid in the coarse textured soils of central Washington and can supply between 50 to 100 kg N ha^{-1} depending on the cover crop incorporated.

Nitrogen fertilizer recoveries, total N uptake and initial and final inorganic N concentrations suggest that

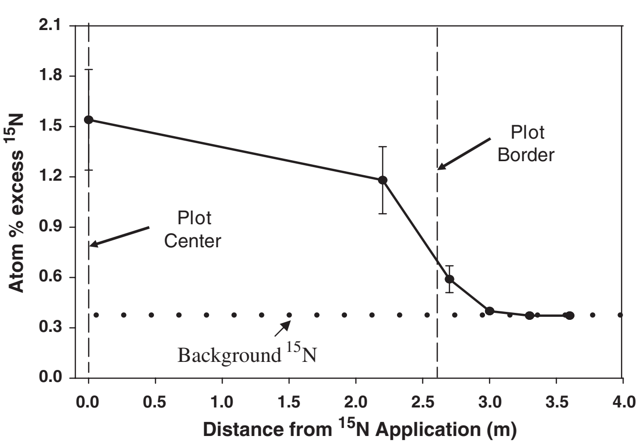

Fig. 4. Change in ^{15}N atom % excess in mustard residues adjacent to labeled microplots in Exp. II.

there is a high rate of N turnover in the system. The N mineralized from the control soils during the incubation study suggest that the monthly rate of mineralization was about 14 kg N ha^{-1} for the control soils vs. 36 kg N ha^{-1} released from the mustard residue during incubation. Although we may have a lower N turnover rate during the winter, the N mineralized from mustard cover crops planted before potato planting may be significant.

Delgado (2001) reported 75 to 227 kg NO_3–N ha^{-1} remained in the 0- to 0.9-m soil profile after potato harvest in irrigated sandy soils. The residual soil NO_3–N after potato harvest for Exp. II was 56 kg NO_3–N ha^{-1}. Residual soil profile inorganic N was 49 kg N ha^{-1} before planting of the mustard cover crop. Fertilizer applications were 56 kg N ha^{-1} applied to the mustard cover crop, 112 kg N ha^{-1} applied at preplant and 263 kg N ha^{-1} in season to the potato crop. We assumed about 5 kg N wet and dry air deposition, about, 14 kg N ha^{-1} from the mineralization of soil organic matter, 36 kg N ha^{-1} from decomposition of mustard residues (Fig. 3) and a potential 33 kg N ha^{-1} mineralized from the decomposition of the previous sweet corn crop residues. Although we did not directly measure some of the pools like atmospheric deposition and corn crop residue mineralization, we can estimate a soil/plant N input pool of 568 kg N ha^{-1}. The N outputs from the system were 325 and 65 kg N ha^{-1} in potato tubers and vines, respectively, and 68 kg N ha^{-1} residual soil inorganic N for a total output of 458 kg N ha^{-1}. The difference between inputs and outputs of 110 kg N ha^{-1} represents N losses and/or stored N not determined (e.g., roots) in the soil profile. The main mechanism for N losses is likely NO_3–N leaching.

This study indicated that this cropping system grown in this irrigated soil is susceptible to N losses because of low N recovery and coarse sandy texture. We suggest that NO_3–N leaching may be the main mechanism driving N losses. We propose that mustard cover crop residues can significantly contribute to reduce N losses and storage through the pool of N sequestered in residues and slower release through decomposition over the cropping season while maintaining yields at this site.

This was the first study to quantify N cycling from a mustard cover crop to potato. This study highlights the importance of the N contribution from a cover crop toward the N requirement of a subsequent potato crop. To reduce losses and increase the N use efficiency in this system, we recommend the use of the winter mustard cover crops. We found that a large portion of the N returned to the soil with the crop residue was still recovered in the soil after 1 yr. We suggest that this N is retained as a component of particulate organic matter derived from crop residue.

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